Definition and Preliminary Design of the

LAWS

Laser Atmospheric Wind Sounder

NASA Marshall Space
Flight Center

GE Astro Space

Hughes Danbury

STI Optronics

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PHASE II
FINAL REPORT VOLUME I

EXECUTIVE SUMMARY

Date: 9/30/92

GE Astro Space
Hughes Danbury
STI Optronics

Contract Number: NAS8-37589

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1.0   INTRODUCTION

The Laser Atmospheric Wind Sounder (LAWS) program was conducted by GE Astro-Space Division, with the support of Hughes Danbury Optical Systems (HDOS), Danbury, CT for the optical subsystem, and STI Optronics, Bellevue, WA, for the laser subsystem. Lassen Research, Manton, CA (receiver subsystem) and Simpson Weather Associates, Charlottesville, VA (mission requirements) also participated in a supporting role. The LAWS contract was managed by the NASA Marshall Space Flight Center and performed in two phases beginning March 27, 1989 and ending September 30, 1992.

1.1   Mission Objectives

Accurate knowledge of winds is critical to our understanding of the earth's climate and to our ability to predict climate change. Winds are a fundamental component of highly non-linear interactions between oceans, land surfaces and the atmosphere. Interactions at these interfaces are the focus of much climate change research.

Although wind information is critical for advancing our understanding, currently most of our description of atmospheric motion is obtained indirectly - i.e., derived from observations of temperature and moisture through geostrophic relationships. Direct measurement of winds over the globe is limited to land-based rawinsonde surface stations and a few ship/aircraft reports. Cloud track winds using satellite imagery are calculated but must be used with great care.

The LAWS mission objective, therefore, is to provide diurnal and global direct observations of winds - an observation that will incrementally enhance our knowledge of the earth's climate and physical processes responsible for its change.

To meet mission objectives, the LAWS instrument and data processors are being optimized to provide a product that is best suited for assimilation into global climate models, regional scale models and numerical weather prediction models. Given that there are constraints on the operation of an active sensor (e.g., power, laser life time, thermal control), the LAWS design must take into consideration:

> that the value of LAWS observations will be measured in terms of <u>incremental</u> impact on man's knowledge.

that LAWS winds will be weighted to other wind observations, both direct and indirect.

that LAWS must give priority to taking observations where there currently are no or incomplete wind observations.

that LAWS should provide enhanced resolution of ageostrophic winds over regions of the globe (e.g., tropics, oceans) not observed by other instruments.

that LAWS should also provide a minimum set of observations, unbiased in space and time, for long term climate analysis.

The system design reported here has assumed a given power, weight and volume allowance for the LAWS instrument. As the study progressed these numbers changed and it is likely that they will change again in the future. With this in mind the GE team has incorporated flexibility into the system design to allow LAWS to be configured for a range of launch vehicles and programmed to achieve the most science for whatever spacecraft resources are eventually made available.

1.2   Study Objectives

The objective of phase I of the LAWS study was to define and perform a preliminary design for the LAWS instrument. The definition phase consisted of identifying realistic concepts for LAWS and analyzing them in sufficient detail to be able to choose the most promising one for the LAWS application. System and subsystem configurations were then developed for the chosen concept. The concept and subsequent configuration were to be compatible with two prospective platforms- the Japanese Polar Orbiting Platform (JPOP) and as an attached payload on the Space Station Freedom.

After a thorough and objective concept selection process, we chose a heterodyne detection Doppler lidar using a CO_2 laser transmitter operating at 9.1 μm over a 2.1 μm solid state system. The choice of the CO_2 approach over solid-state reflects the advanced state of development of CO_2 lasers, its maturity in ground-based systems and the eased subsystem requirements associated with the longer wavelength.

The CO_2 lidar concept was then analyzed in detail to arrive at a configuration for the instrument and its major subsystems. Our approach throughout the configuration design was to take a systems perspective and trade requirements between subsystems, wherever possible, to arrive at configurations which made maximum use of existing,

proven technology or relatively straightforward extensions to existing technology to reduce risk and cost. At the conclusion of Phase I we arrived at a configuration for LAWS which meets the performance requirements, yet which is less complex than previous designs of space-based wind sensors (e.g. Windsat), employs lightweight technologies to meet its weight goal (<800 kg) and sufficiently flexible to offer various operational scenarios with power requirements from about 2 kW to 3 kW. The Phase I Final Report was released in March 1990.

The 21-month Phase II began in October 1990. The requirement to accommodate LAWS as an attached payload on Space Station Freedom was deleted and the orbit altitude for the Japanese polar orbiting platform was changed from 824 km to 705 km. The power allocated to LAWS was reduced to 2.2 kW from 3 kW. Subsequently the availability of a Japanese Polar Orbiting Platform was called into question and LAWS accommodation studies were continued using a conceptual, ATLAS-launched platform supplied by MSFC. In March 1991 a modification to the original contract was funded to provide a LAWS laser breadboard which could demonstrate all the performance requirements of the LAWS laser. Also funded as part of the same contract extension was a lifetest demonstration using an existing laser at STI. The breadboard extension was an eighteen month effort and the period of performance was therefore extended to September 30, 1992.

1.3   Highlights of the Phase II Study

The Phase II design configured for the MSFC supplied bus is shown in Figure 1-1. The main interface between the instrument and platform is a graphite-epoxy optical bench which maintains the strict alignment tolerances between the laser and optical subsystems. Support subsystem components and electronics boxes are mounted to the side of the optical bench on platform provided cold-plates. Laser heat is rejected via heat exchangers mated to cold plates under the optical bench. This configuration minimizes the amount of instrument structure yet allows LAWS to be integrated and tested prior to integration with the platform. The configuration is easily adaptable to other platforms and launch vehicles. The major subsystems draw on existing technology or heritage where possible and all have been subject to risk retirement activities during the 4 years of the LAWS program.

The phase II **laser** design (shown in the figure) is based on lasers which have demonstrated that they can meet the requirements of operational Doppler lidars. The NOAA Doppler system, which uses an STI supplied laser, has been operating since the early '80's. A ground-based mobile system constructed at GE during the LAWS program

uses a 2-J laser based on the NOAA design but with upgrades to improve the beam quality and efficiency. The upgrades resulted in an intrinsic efficiency of 6.3% for the GE laser. This is a significant result given that the goal of the LAWS phase II design is for a wallplug efficiency of 6%. CORA (MIT-Lincoln Laboratory) is the largest Doppler lidar in existence and uses an STI supplied 200-J laser of similar (although physically much larger) design to the NOAA and GE devices.
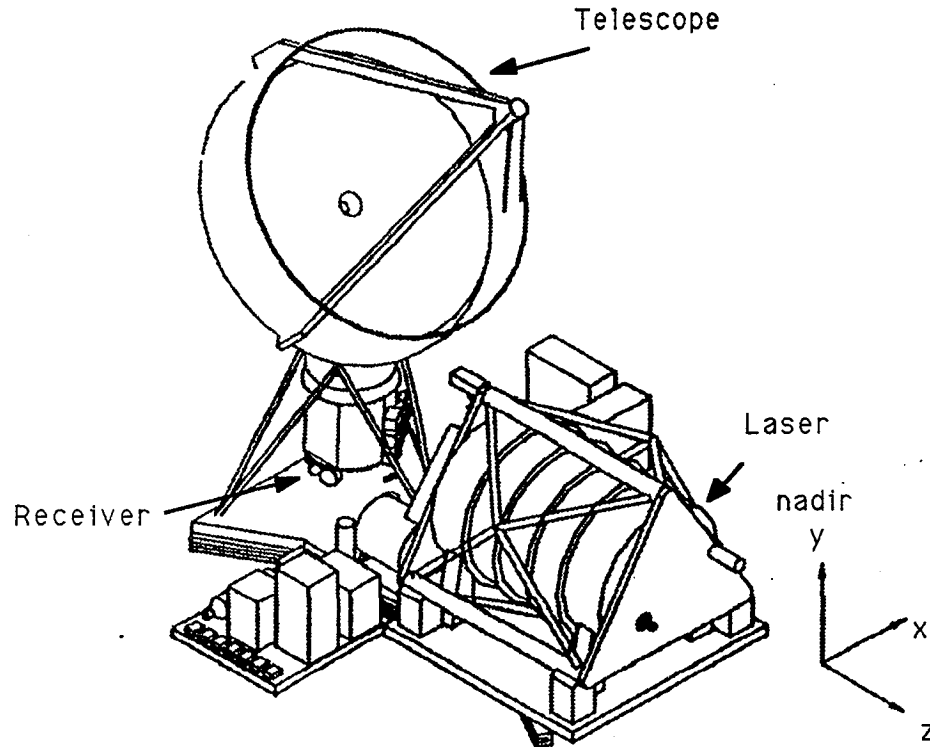
Figure 1-1 LAWS Instrument Configuration

At the beginning of the LAWS program it was recognized that the biggest challenge to CO_2 lasers was achieving the life requirement of 10^9 pulses. The demonstration in May 1992 of 10^8 pulses from the LAWS life-testbed laser at STI has shown that there are no unforeseen barriers to achieving long-life. The data generated by this important demonstration will be invaluable in designing the LAWS phase C/D laser.

The design of the LAWS **optical system** has been facilitated throughout by HDOS-developed code which predicts the impact on system SNR in terms of optical parameters such as despace and decenter. Also the error budget allocations for the pointing and control subsystem have been substantiated by measurement (e.g. the bearing runout was measured for a typical LAWS-type bearing) or by data available from other programs.

The optical system largely determines the LAWS envelope. The fact that it is compact allows us to package LAWS very efficiently and we were not only able to show LAWS configurations in the Atlas vehicle as required, but also in a Delta vehicle, with no compromise on performance.

The **receiver subsystem** uses a HgCdTe detector in the focal plane of the optical subsystem which must operate at a bandwidth in excess of 1 GHz (due to the motion of the spacecraft). GE investment in HgCdTe detectors and coplanar waveguides over the course of the LAWS Study has resulted in an increase in quantum efficiency of about 3 dB at the high bandwidths required.

Finally, the GE team investment, which developed extensive, detailed computer models to predict the performance of the LAWS system and subsystems, provides an infrastructure and basis from which to investigate alternate configurations and proceed with phase C/D system design.

2.0   SYSTEM OVERVIEW

System trades were performed in both Phases I and II (using existing performance model codes) to define ranges of possible values of the major LAWS parameters: laser energy, telescope aperture, laser repetition rate, laser pulse length, scan nadir angle and scan rate. A maturing understanding of the signal-to-noise-ratio (SNR) and coverage required to achieve the desired velocity accuracy, then constrained the values of those parameters to a certain range, for a given set of spacecraft resources. The statement of work (SOW) was amended as the Study progressed to reflect this new understanding. Figure 2.-1 shows, at its center, the derived instrument requirements as they eventually appeared in the SOW for Phase II, with their relationship to the top-level science requirements around the outside.

The instrument specification developed to meet the science and instrument requirements is shown in Table 2-1. The main parameters specified were: laser pulse energy, telescope aperture, scan rotation rate, and the maximum laser repetition rate. The laser pulse length, asynchronous operation, and nadir scan angle are given in the SOW, and were defined previously. The relationship of the derived design parameter, the value, and the driving requirement are summarized in the Table .
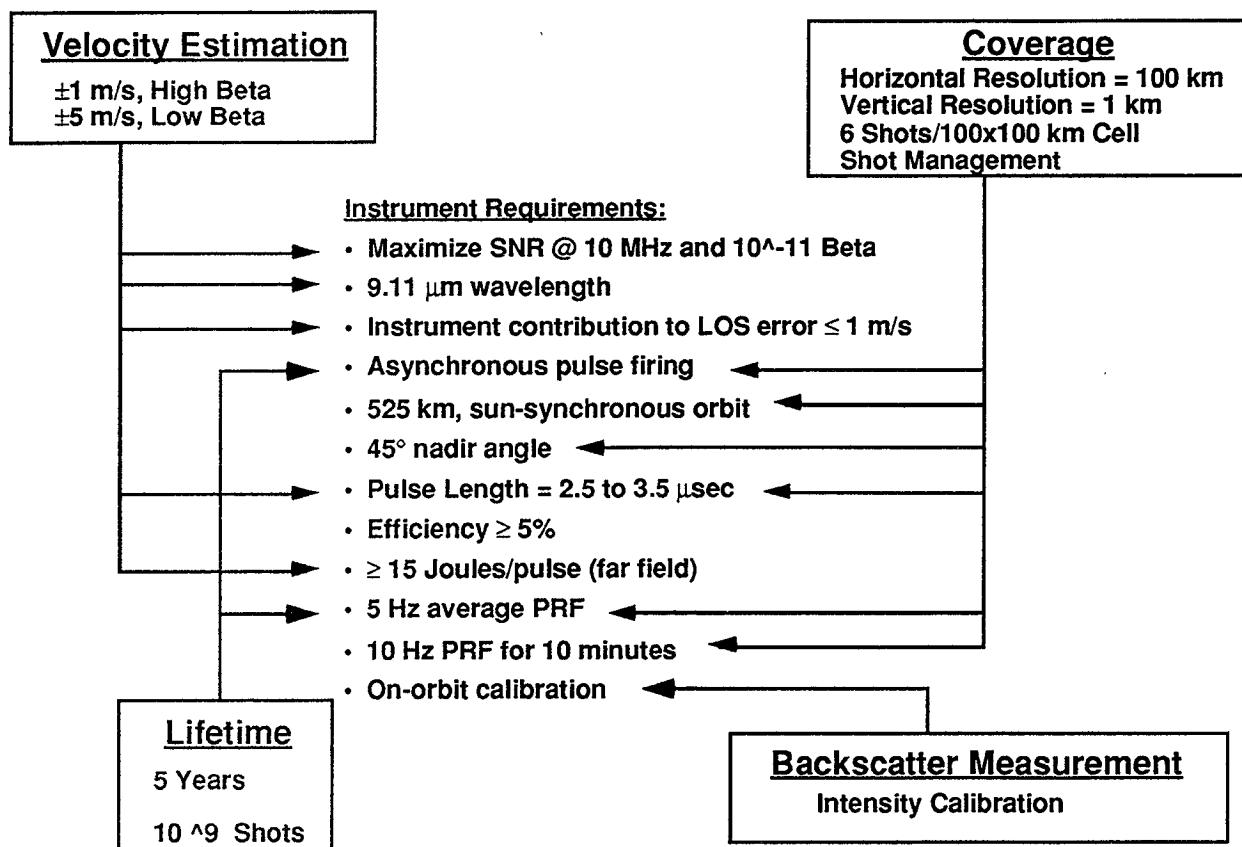
Velocity Estimation

±1 m/s, High Beta
±5 m/s, Low Beta

Coverage

Horizontal Resolution = 100 km
Vertical Resolution = 1 km
6 Shots/100x100 km Cell
Shot Management

Instrument Requirements:

- Maximize SNR @ 10 MHz and 10^-11 Beta
- 9.11 μm wavelength
- Instrument contribution to LOS error ≤ 1 m/s
- Asynchronous pulse firing
- 525 km, sun-synchronous orbit
- 45° nadir angle
- Pulse Length = 2.5 to 3.5 μsec
- Efficiency ≥ 5%
- ≥ 15 Joules/pulse (far field)
- 5 Hz average PRF
- 10 Hz PRF for 10 minutes
- On-orbit calibration

Lifetime

5 Years

10^9 Shots

Backscatter Measurement

Intensity Calibration

Figure 2.-1 Science and Instrument Requirements

Table 2.-1 Top Level Instrument Specifications

Parameter	Value	Driver
Useful Pulse Energy	15 Joules	Performance, Power, Weight
Optics Aperture	1.5 meters	Size, Weight
Pulse Length	3 μsec	Laser Efficiency
Scan Rotation Rate	12 RPM	Various
Scan Nadir Angle	45 degrees	Coverage, SNR
Laser Repetition Rate	Asynchronous, up to 20 Hz	Coverage

The LAWS System block diagram, detailing the subsystems and internal and external data flow interfaces, is shown in Figure 2-2. Some of the instrument/Platform interfaces, such as the Bus Data Unit (BDU) for data and the Bus Select Relay (BSR) for power are provided as GFE for integration with the instrument. The Transfer Frame Generator (TFG, also assumed GFE) is the interface between the instrument high-rate

science data and the Platform. The laser fluid loop interfaces with the Platform at a heat exchanger, which is mated to a Platform coldplate.
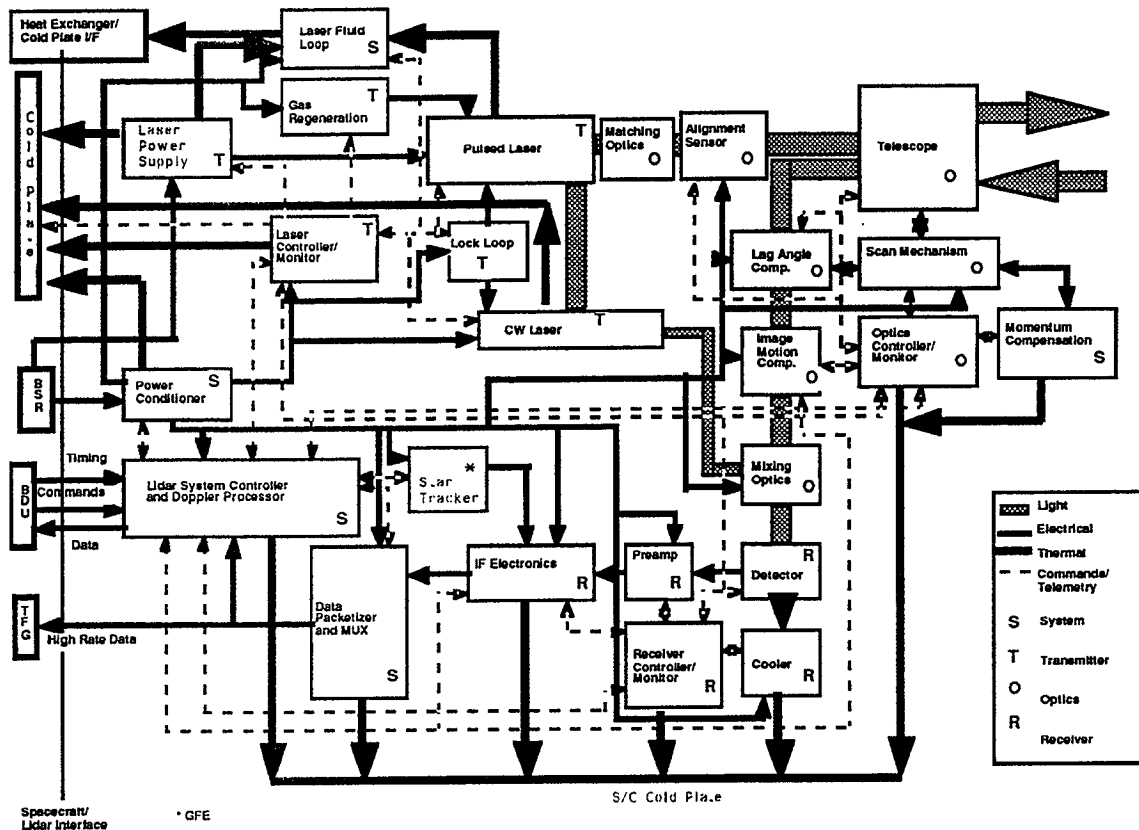

Figure 2-2 System Functional Block Diagram

Preliminary weight estimates of the LAWS subsystems are shown in Figure 2-3.

The power requirements for LAWS consist of a fixed or overhead power plus an amount which varies depending on the laser repetition rate. Power requirements are shown in Table 2-2 for two example modes of operation of the instrument. The actual mode of operation (i.e. the repetition rate of the laser) will vary up to a peak of 20 Hz as LAWS progresses around its orbit. For the 2 examples shown, the Survey Mode operating at a nominal rate of 5 Hz provides approximately 6 shots per 100 km x 100 km grid square at the ground while the High Rep Rate Mode operates at 10 Hz for placing a higher density of shots in regions of interest. The length of time for which the High Rep Rate Mode can be used is limited by the thermal subsystem to about 10 minutes per orbit.
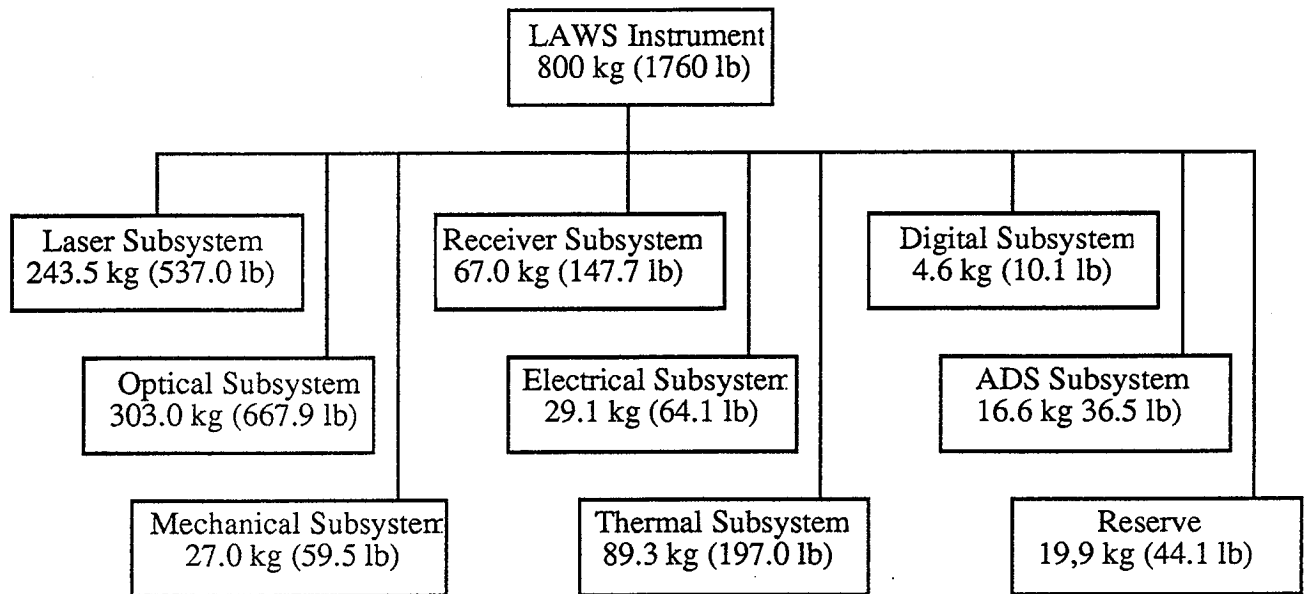
Figure 2-3 LAWS Subsystem Weight Estimates

Table 2-2 LAWS Electrical Power Requirements

Subsystem	Survey Mode		High Rep Rate Mode	
	Avg. Power (5 Hz) (W)	Peak Power (7.5 Hz) (W)	Avg. Power (10 Hz) (W)	Peak Power (15 Hz) (W)
Optics	127	127	127	127
Laser	1340	1985	2630	3920
Receiver	140	140	140	140
Electrical	80	80	80	80
Digital	22	22	22	22
ADS	23	23	23	23
Thermal	200	200	200	200
Reserve (15%)	290	387	483	677
TOTAL	2222	2964	3705	5189

The LAWS major subsystems are discussed in the following sections.

3.0   OPTICAL SUBSYSTEM

The overall function of the LAWS Optical Subsystem is to expand the laser beam and direct it toward the atmosphere in a conical scan, to receive the backscattered radiation, compensate for the lag angle and any jitter, mix the received, stabilized beam with the local oscillator, then focus the combined beams on the receiver detector. In addition, the optical sub system functions include certain diagnostic and correction operations. The Optical Subsystem Block Diagram is shown in Figure 3-1.
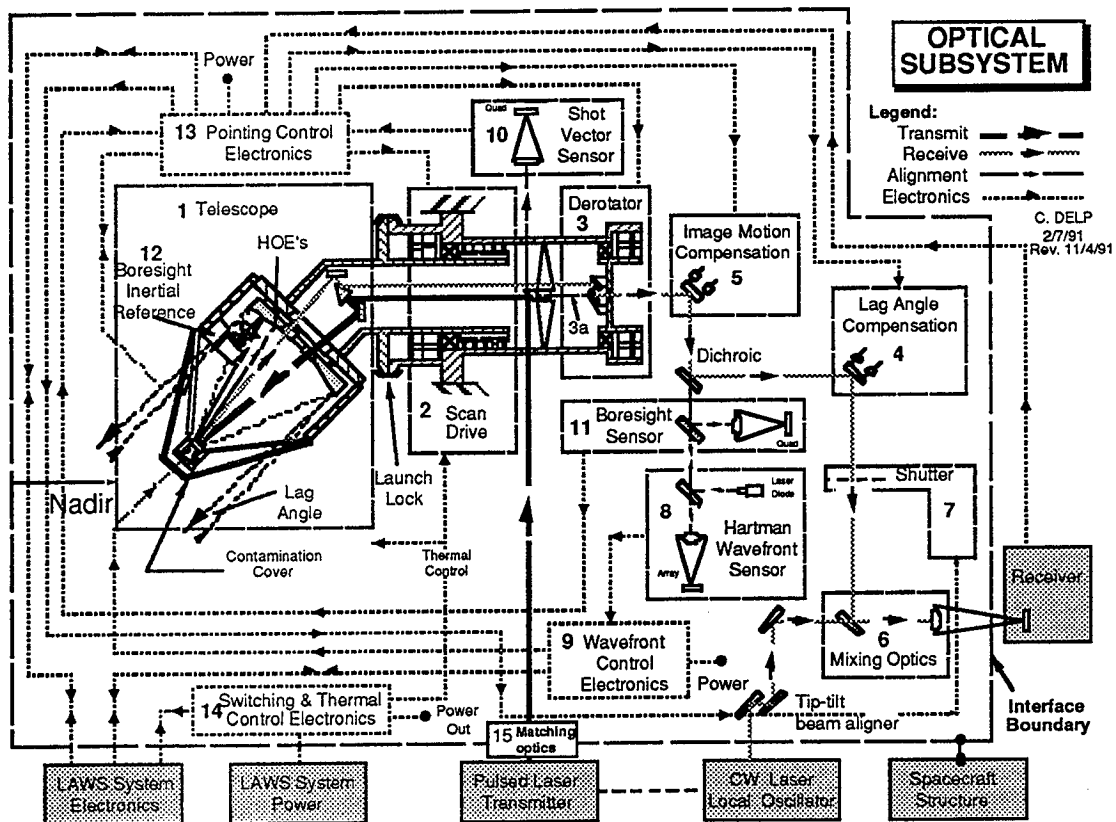

Figure 3-1 Optical Subsystem Block Diagram

The LAWS Telescope is an afocal, two mirror, confocal parabola system which serves both as the transmitter laser beam expander and as the receiver collecting telescope. The baseline Telescope magnification is 33x. The Telescope is scanned in azimuth around the nadir axis at 12 rpm and is mounted to the Scan Drive at a fixed 45° angle from nadir, resulting in a conical scan with an included cone angle of 90°. The Primary Mirror (PM) is 1.5 m diameter, has an f/No. of 1.0 and contains two holes, off-set on either side of center, to provide for penetration of the transmit and receive beams.

The angular separation between the transmit and receive beams results from the continuous azimuth motion, the time delay between transmit pulse and reflected "echo", and the magnification of the Telescope.

The preliminary configuration design that evolved through the Phase 2 study effort is shown isometrically in Figure 3-2.
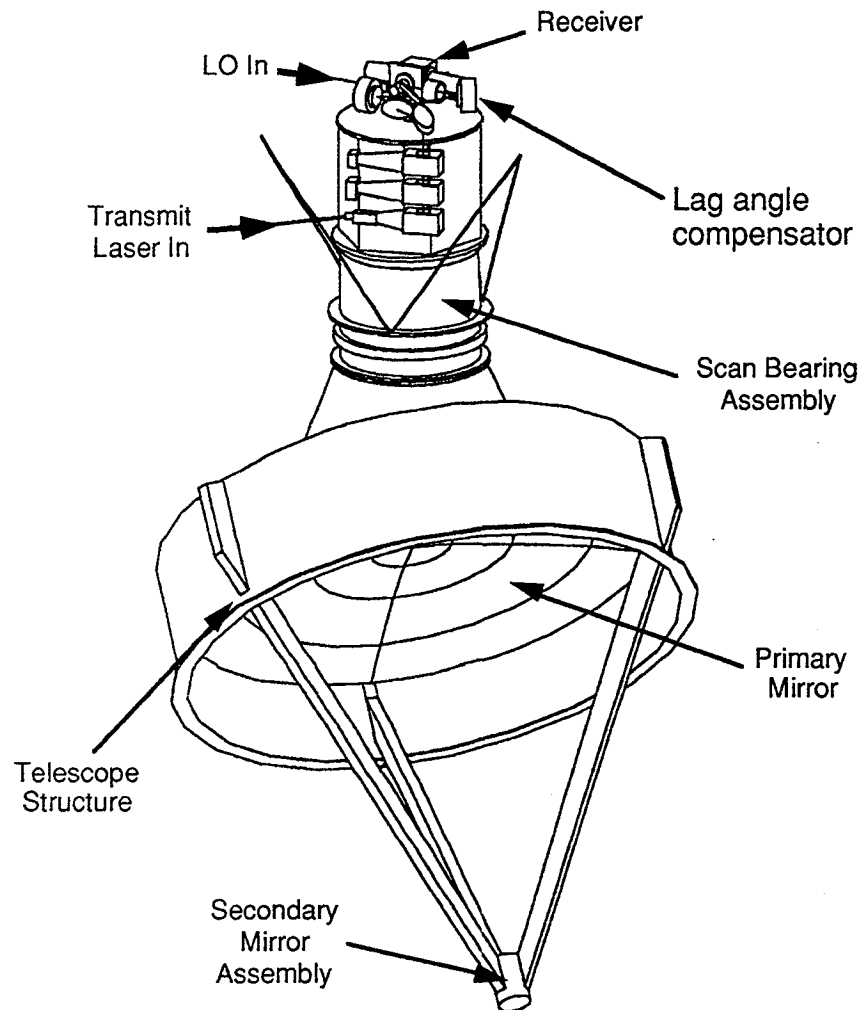
Figure 3-2 Optical Subsystem Baseline Design

The heart of the design is an adaptation of the Hughes Aircraft bearing and power transfer assembly (BAPTA), developed for use on their line of commercial communications satellites. Approximately 80% of the existing design is incorporated in the LAWS configuration. A detailed illustration of the LAWS BAPTA is shown in Figure 3-3. The locations of the outgoing laser beam and the local oscillator beam are indicated on the drawing. The receiver, along with its cooler, is mounted on the "top hat" optical bench at the position indicated.
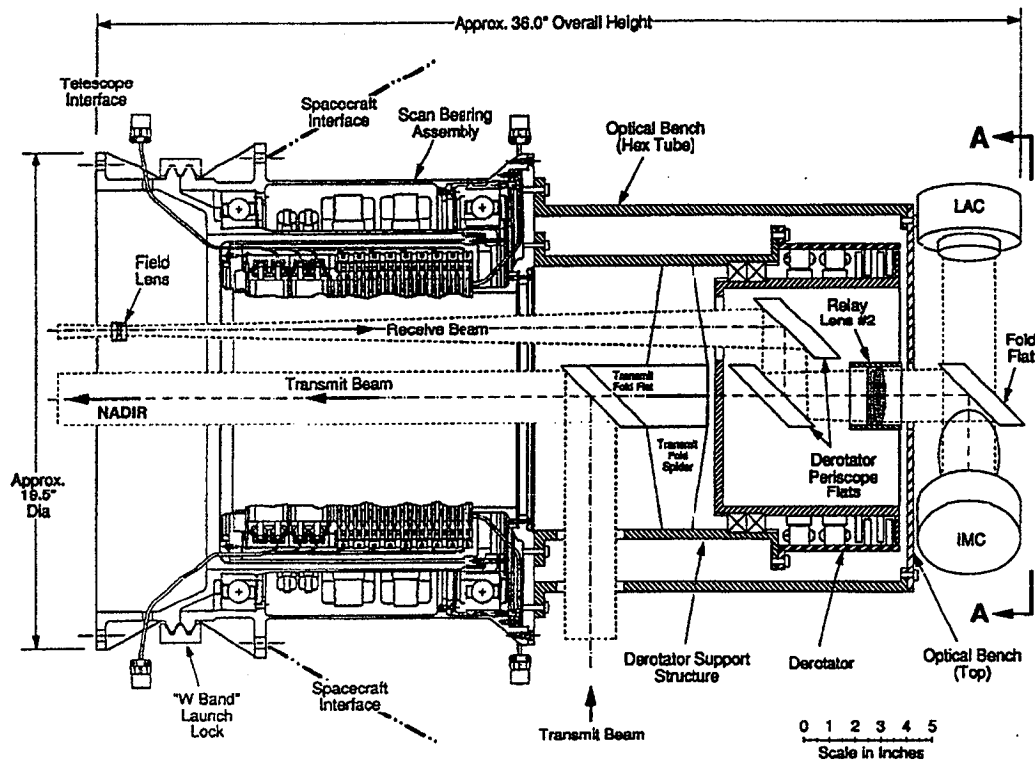
Figure 3-3 Scan Bearing/Derotator/Optical Bench Assembly Configuration.

The Scan Bearing Assembly on the left side of the illustration is a derivative design of the Hughes space-proven HS A-10 BAPTA (Bearing and Power Transfer Assembly). The HS A10 BAPTA meets the power, signal, and run-out requirements of LAWS. The HS A-10 design has been modified to provide a hollow bore through the shaft for the transmit and receive beams. It includes the bearings, motors, encoders and sliprings required to perform the conical scan and to transfer utilities across the rotating interface to the telescope. Electrical functional redundancy is provided to preclude single-point failures. An integral flange on the outer housing near the left hand bearing provides a hard point for attachment of the telescope assembly. Between the two flanges is a "W" band clamp launch lock which prevents rotation of the telescope during launch, unloads the bearings, and provides a by-pass launch load path around the bearings.

Hughes Aircraft's Space and Communications group has gained significant experience in designing and producing bearing and power transfer assemblies for their line of spinning communications satellites and HDOS bring this technology to the LAWS program. It is worth noting that there have been no on-orbit bearing failures in over 75 satellites with an average life of 11 years.

4.0   LASER SUBSYSTEM

The laser subsystem consists of all the components required for the generation and frequency control of two CO_2 laser beams, the transmitter and local oscillator. The selected transmitter architecture is the external injection of a transversely excited, transverse flow oscillator incorporating an unstable resonator cavity. The external injection selection is based on the heritage of this approach for long-range wind sensing, and in its high-power potential, since the high gain possible with this design allows an unstable mode to be generated. This results in efficient use of the gain medium.

The transmitter laser generates a continuous train of single frequency pulses (15 J, 3 µsec) at an average rate of 5 Hz (20 Hz peak), that is delivered to the optical subsystem for transmission to earth. The frequency of the transmitter laser is controlled by injecting it with a sample of a 5-Watt, highly-stable, continuous-wave (cw) laser beam. Another sample is delivered to the receiver subsystem to function as the local oscillator beam.

The Laser Subsystem preliminary design is depicted in the isometric drawing of Figure 4-1. The Gain Module (cylindrical vessel) is attached to the system platform via supports that incorporate vibration isolators. The (triangular cross-section) optical truss, to which the Laser Subsystem optical benches are attached, is draped over the Gain Module and is hard-mounted to the System platform. The control and diagnostics and high-voltage power supplies (for the Gain Module pulse forming network) are located on the platform cold plates. Umbilicals connect the gain module heat-exchanger, optics, CW laser and acousto-optic cooling loops to the laser fluid loop and also the components requiring electrical power to the system bus. A Gain Module cross-sectional drawing is shown in Figure 4-2.

Self sustained discharge excitation of the gas was chosen for reasons of simplicity and efficiency, and was supported by experiments at STI conducted under a program jointly funded by the NASA Marshall Space Flight Center and the Air Force Geophysics Laboratory. This investigation provided measurements of the laser gain coefficient and collisional relaxation rates for the $^{12}C^{18}O_2$ rare isotope gas mixtures, which were used in our laser modeling and scaling studies, and also produced efficiencies of the self-sustained and e-beam sustained discharge approaches. Intrinsic efficiencies exceeding those measured using the e-beam sustained approach were observed.
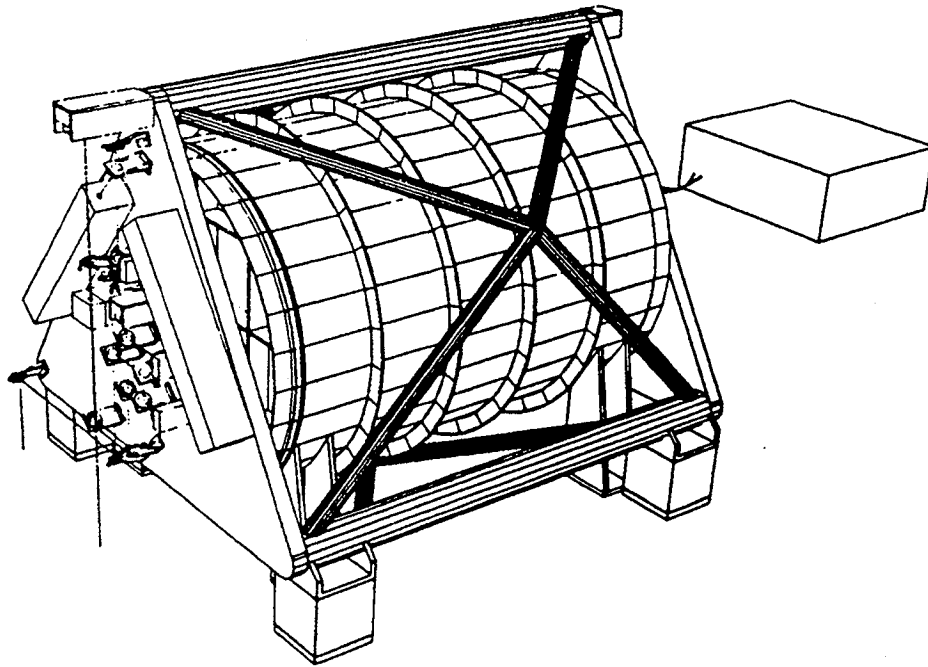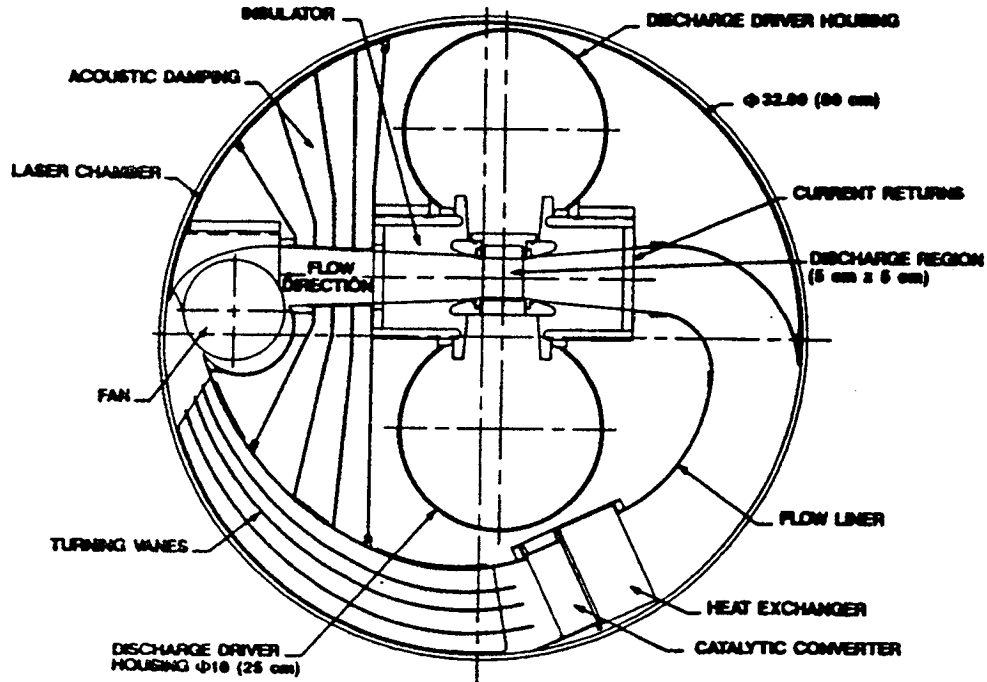
Figure 4-1 Laser Subsystem Isometric Drawing

Figure4-2   Laser Gain Module Cross Section

Pulse profile predictions using the measured kinetic rates in conjunction with STI laser kinetic codes are in excellent agreement. The parameters of the transmitter gain section were established using these codes, and used as the basis for the configuration development and size-weight-efficiency estimations. The baseline configuration uses a gas mix of 3 parts He, 2 parts N_2 and 1 part CO_2 (3/2/1), the same as was used in the MSFC/AFGL Study.

The optical components including the laser resonator and beam sampling and control optics are vibrationally decoupled from both the gain module and the instrument platform such that they experience a quiescent vibrational environment. Figure 4-1 shows the graphite-epoxy truss structure that supports the optical benches at either end of the transmitter gain module. The unstable resonator configuration selected uses a graded reflectivity mirror for the feedback/output coupler because of superior mode discrimination and the excellent output beam quality characteristics of this arrangement, e.g. the >80% conversion of the transmitted energy into the central lobe in the far field. A fixed frequency waveguide laser was chosen as the injection/local oscillator for reasons of simplicity and robustness. Our design includes a second unit for redundancy.

The laser breadboard program discussed in section 7.0 uses the same resonator architecture as the LAWS Phase II design.

5.0 RECEIVER SUBSYSTEM

The primary function of the Receiver Subsystem is to measure the Doppler shift of the laser energy reflected from the atmosphere. This Doppler shift is measured as an RF beat frequency between the reflected signal and the local oscillator (LO) radiation and is detected on the baseband 9.11 μm wavelength. The Doppler shift due to the spacecraft motion and the Earth rotation must be removed by the intermediate frequency (IF) electronics. The receiver then digitizes and stores the raw data for use in the system signal processor and for downlink.

The three major constituents of the Receiver Subsystem are shown in the block diagram of Figure 5-1. The detector is a five-element array which both detects the return signal and determines the alignment of the image for compensation of long term image drift. The dewar housing includes the detectors, the dual Split-Stirling Cryocooling System, and the IF electronics. The Mercury Cadmium Telluride (MCT) detectors are housed within a cryogenic dewar and maintained at a 77K operating temperature. These detectors are photovoltaic diodes, and produce an RF signal corresponding to the mixing of the LO and the reflected signal. The pre-amps located on the outside of the dewar housing amplify this signal for input to the IF electronics. The IF electronics remove the

spacecraft velocity and Earth rotation from the signal, and further process the signal into I and Q components. The IF electronics then digitizes and buffers the signal for use by the Doppler Processor in the Digital Subsystem.
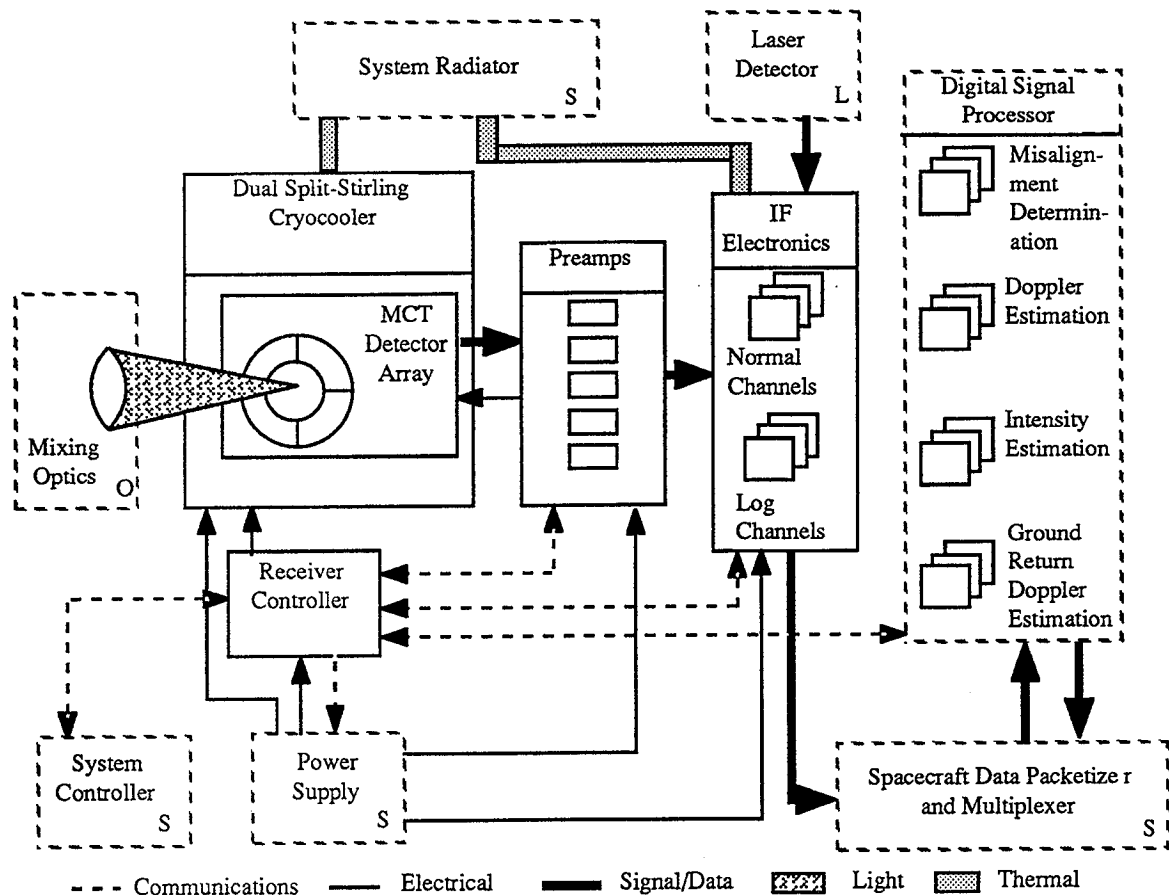

Figure 5-1 Receiver Subsystem Block Diagram

The dewar is cooled by a pair of Split-Stirling cryocoolers. The top view of the dewar is shown in Figure 5-2. The system consists of four cyrocoolers- only two opposing coolers are operational, and the other two are included for redundancy. The cylindrical design of the dewar ensures that vibrations due to the cooler displacers are not translated to the detector mounts. This dewar design has a natural frequency of greater than 2000 Hz which will be insensitive to the 40 Hz driving force of the displacer.
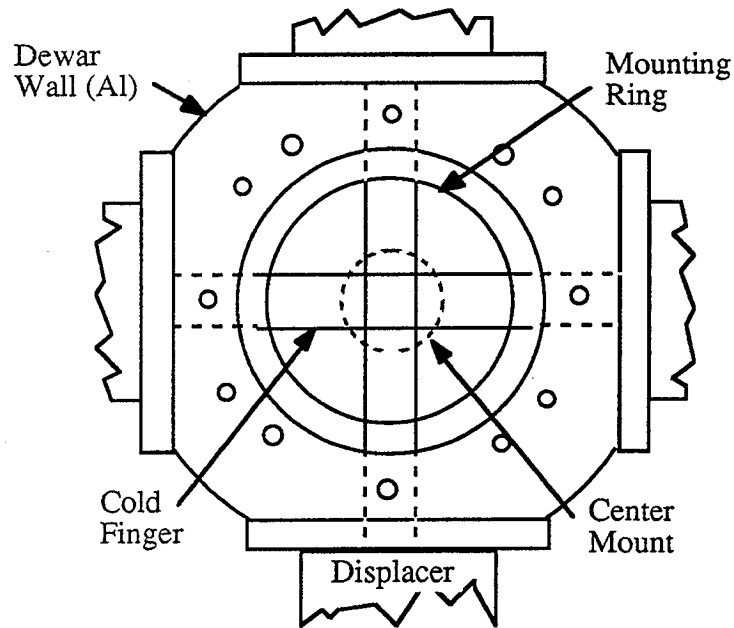
Dewar
Wall (Al)

Mounting
Ring

Cold
Finger

Center
Mount

Displacer

Figure 5-2 Dewar Top-View

The cooling system chosen as the baseline for system design purposes is the British Aerospace 80K Stirling Cycle Cooler (similar to one currently flying on the Upper Atmosphere Research Satellite) shown in Figure 5-3. This system consists of a displacer and a compressor connected by a coolant transfer tube. The system operates in a closed cycle, and does not require any expendable cryogenic cooling agent. A single cooler operating between 80K at the cold finger and 300K ambient can remove a heat load of 0.8 Watts. A pair of coolers, therefore, is more than adequate for handling the anticipated heat load of 1.18 W.

The receiver electronics consist of the bank of preamplifiers, each connected directly to a detector element, and associated IF electronics. The baseline preamplifier design is a silicon bipolar device. The 5 amplifiers are mounted on the outer dewar wall where the temperature is ambient, approximately 300K.

The first function of the IF electronics is to remove the Doppler shift due to the spacecraft motion and that due to the Earth's rotation. A synthesized RF source and a 100 MHz yittrium-indium-garnet (YIG)-tuned bandpass filter serve this purpose. The LO mixes the signal down to a central frequency of 100 MHz chosen to provide a sufficient guard band around the 40 MHz-wide signal centered at 100 MHz. The mixer is followed by a second amplifier and a bandpass filter centered at 100 MHz and two more stages of amplification separated by a limiter. The signal is then split into I and Q channels. These signals are passed through a low pass filter before being digitized by the A/D Converter

and passed to the Digital Signal Processor. The A/D sampling rate has been set at 75 MHz to cover the entire frequency range of the signal.
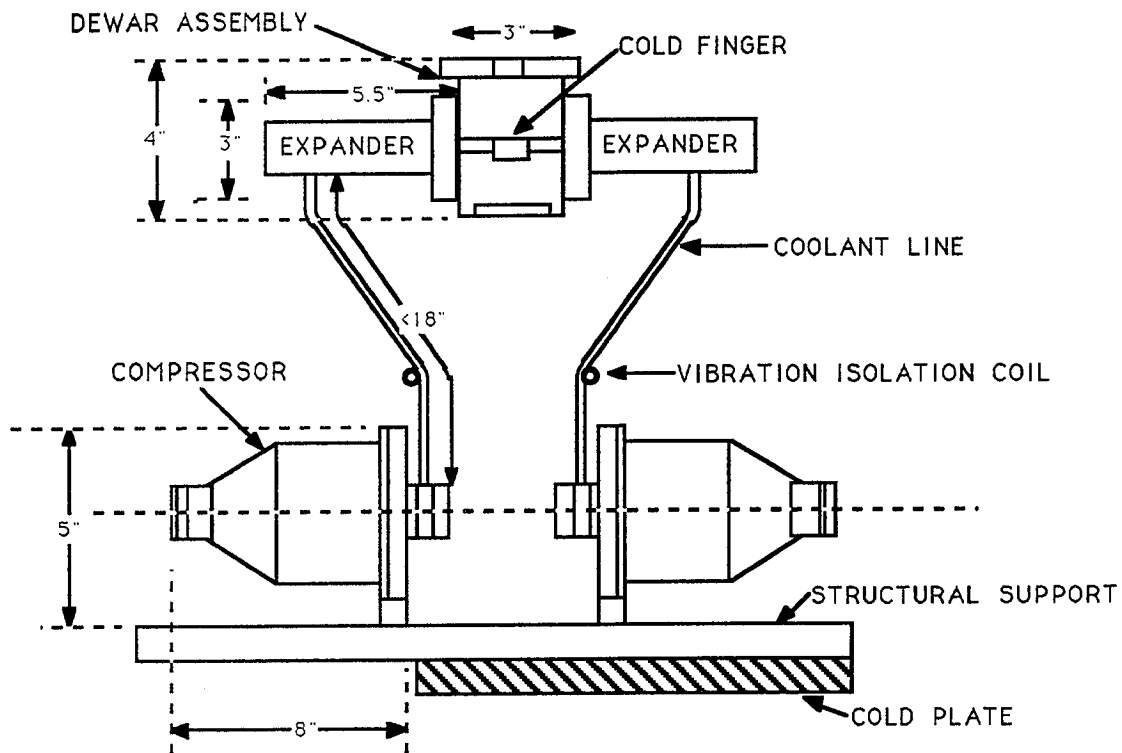

Figure 5-3 Detector Cooler Subsystem

6.0 SYSTEM PERFORMANCE

The LAWS instrument will fly in a polar, sun-synchronous 525 km. altitude orbit. The telescope is scanned at an angle of 45 degrees about nadir with a scan rate of 12 RPM. This combination of scan rate and scan angle were chosen after detailed analyses to maximize both coverage and LOS SNR.

The 12 RPM scan rate, 525 km. altitude, and 45° scan angle results in approximately 6 shots per 100 km x 100 km cell for an average repetition rate of 5 Hz. Figure 6-1 shows the ground track for the baseline case. The large grid squares are the 100 km x 100 km boxes while the smaller squares along the scan ground track are the shot positions. The laser is firing with a 1/cos azimuth-dependent algorithm with a peak shot rate of 7.5 Hz and an average rate of 5 Hz (Survey mode). It can be seen that, on average about 5 to 6 shots fall in each grid square. The High rep rate mode, nominally 10 Hz average, results in about 12 shots per resolution cell. Figure 6-1 also shows that a single scan swath covers about 1100 km. on the ground. Each successive orbital ground track is separated by about 2650 km.
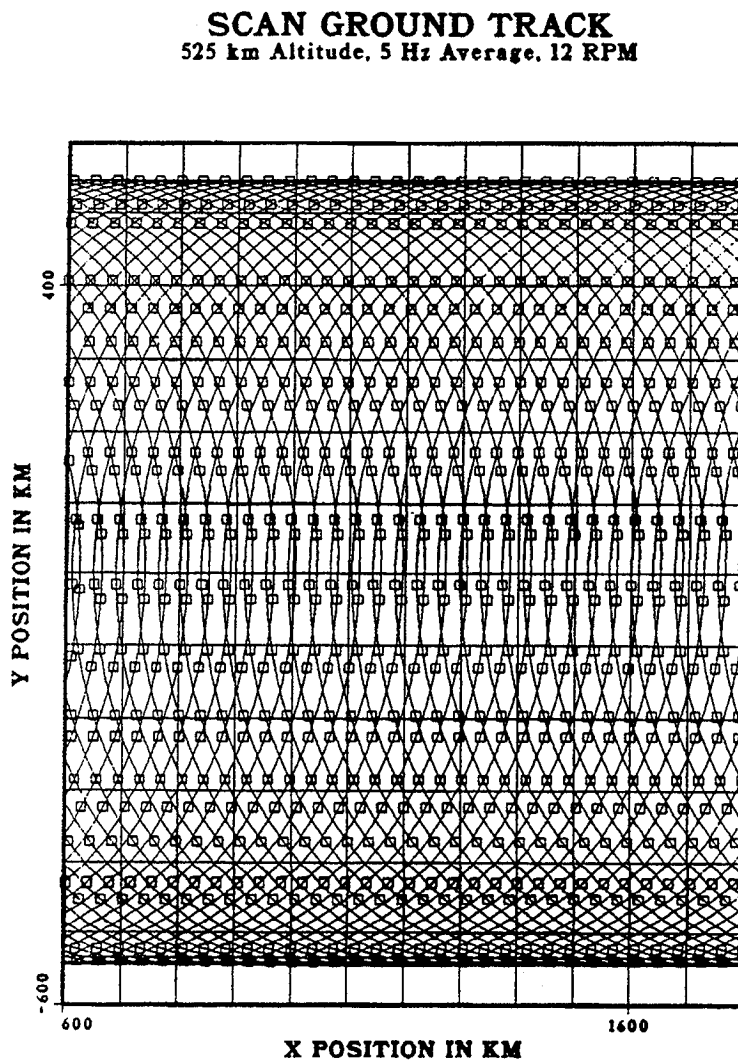
SCAN GROUND TRACK
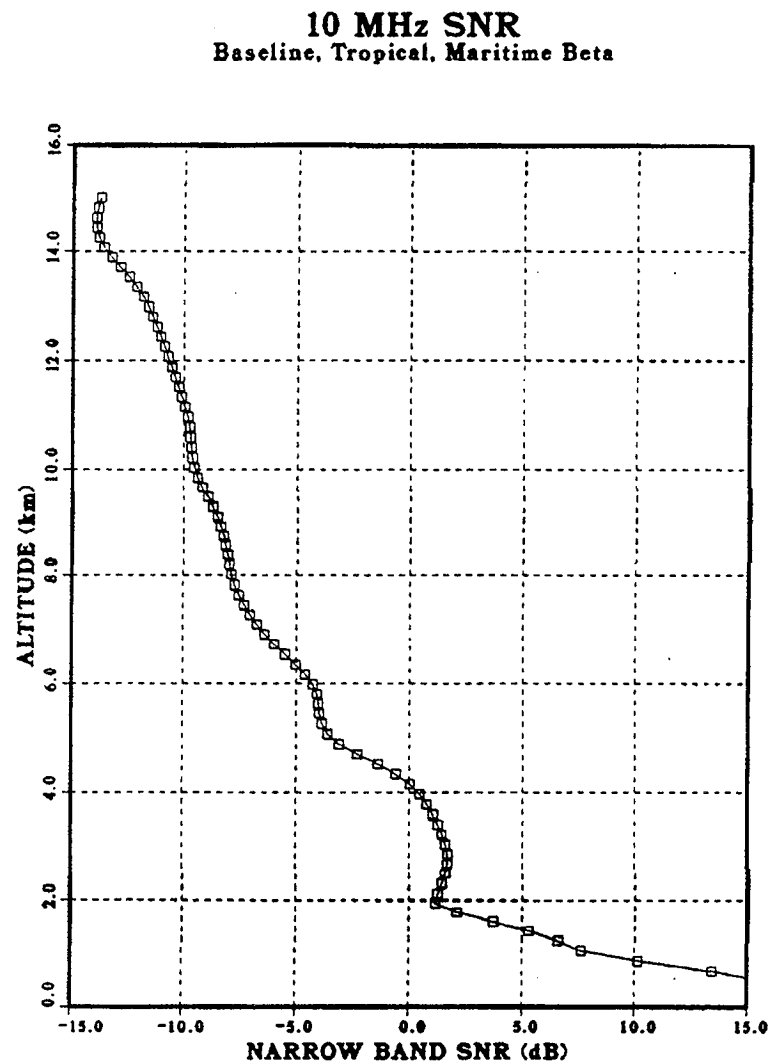### 525 km Altitude, 5 Hz Average, 12 RPM

Figure 6-1 Scan Ground Track

The line-of-sight signal-to-noise-ratio (SNR) for LAWS is presented in Figure 6-2. The Figure shows the wideband (10 MHz) SNR varies from a low of about -14 dB in the upper troposphere to greater than 15 dB at the surface.

10 MHz SNR
Baseline, Tropical, Maritime Beta

Figure 6-2 LOS SNR Estimate

Analysis by the LAWS Science Team has shown that a wideband (10 MHz) SNR of around -10 to -11 dB is required in order to achieve 50% of the velocity errors < 1 m/s. The baseline performance shows, therefore, that for altitudes up to about 12 km the LAWS instrument will provide velocity errors less than about 1 m/s 50% of the time.

7.0 LASER BREADBOARD PROGRAM

The LAWS Laser Breadboard program is designed to generate a database to facilitate the optimization of parameter selection, choice of technological approaches and generation of detailed engineering requirements for the flight hardware. It consists of two components: the Performance Laser Breadboard and the Life-test Breadboard respectively, the goals of which are:

Performance Laser Breadboard

The manufacture and test of a full-scale (LAWS parameters) laser transmitter to demonstrate integrated performance and to validate technological approaches.

Life-test Breadboard

The conduct of long-term tests in an existing facility (the STI CO_2 Laser Test-bed or CO2LT) to address gas life and component reliability issues at the 10^8-shot level and at an elevated pulse repetition rate of 35 Hz.
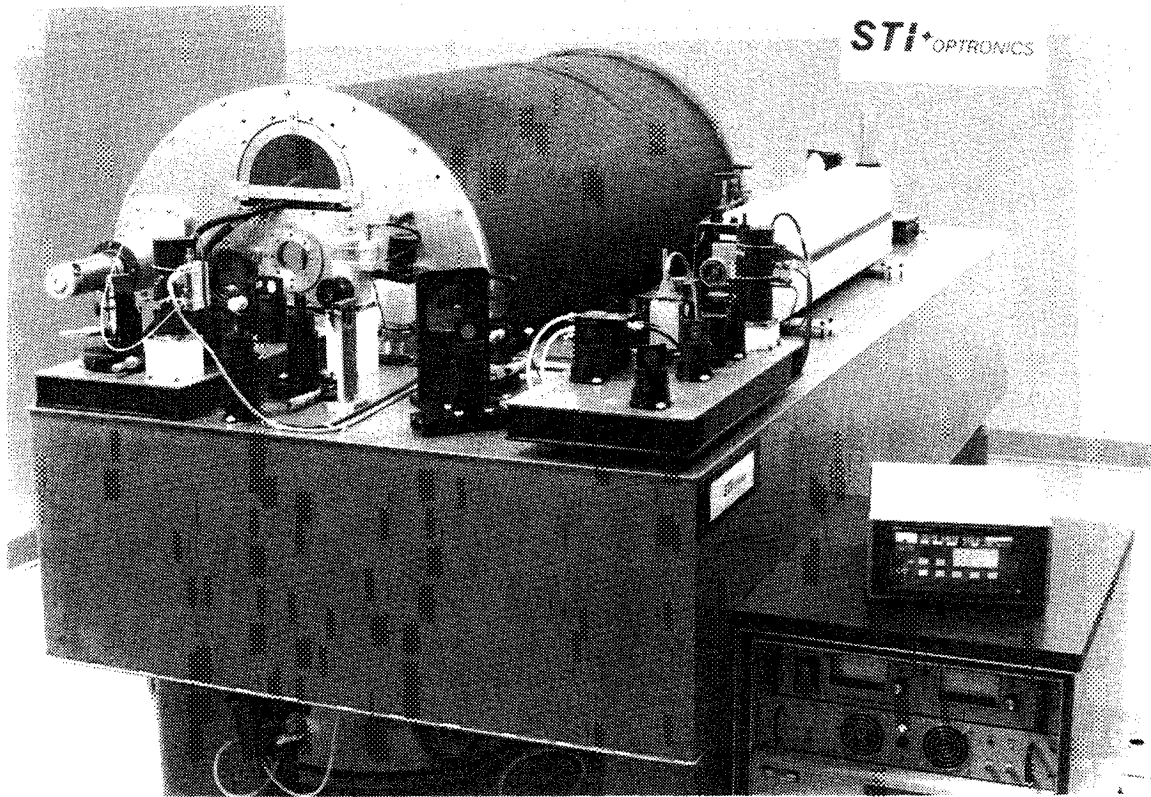
7.1 Performance Breadboard

The requirements for the LAWS Laser Breadboard were developed from system wide considerations and are shown in Table 7-1. Note, that these requirements have been achieved on other STI-constructed Doppler lidars, but not necessarily simultaneously. The Laser Breadboard within the laboratory at STI Optronics is shown in Figure 7-1.

Table 7-1 LAWS Laser Breadboard Requirements

REQUIREMENT	MINIMUM (Simultaneous)	GOAL (Single Parameter)
Energy per pulse (useable)	>15 J	20 J
PRF	10 Hz	20 Hz
Beam Quality	1.2x diffraction limited	1.2x diffraction limited
Beam Jitter	0.1 λ/D	0.1 λ/D
Frequency Chirp	< 150 kHz	< 200 kHz
ηwall plug	traceable to 5.5%	traceable to 5.5%
ηintrinsic	8.0%	8.0%
Chemical Steady State	at 5 Hz (worst case)	at 10 Hz
Energy Stored	190 J	240 J

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

Figure 7-1 Perspective Photograph of Performance Breadboard Laser

The measured pulse energy for the laser in the baseline configuration (injected via a grating, outcoupled via the graded coupler and tuned to a wavelength of 10.6 μm) is 6 J. The pulse energy is currently being limited by the gain module coating, grating efficiency and graded coupler reflectivity losses due to operation at the 10.6-μm wavelength vs the design wavelength at 9.11 μm. There is also evidence that the grating loss is significantly higher than manufacturer specification for the configuration in which it is being used. This evidence is based on measurement of the pulse energy when the grating is replaced by a concave mirror. The >15 J reading obtained exceeds the 15 J goal for the Performance Breadboard. Currently when operating in this configuration the laser is not being injected, so that it oscillates simultaneously on many longitudinal modes. Single-tranverse-mode operation was observed, however. Typically the sum of the energies in all the longitudinal modes transforms into a single longitudinal mode during injection. When both the grating and output coupler were substituted by a set of stable resonator

optics the observed pulse energy increased to >22 J. However, this energy includes the contribution of several transverse modes.

The power spectral density of the laser pulse centered at 60 MHz is shown in Figure 7-2. The energy is concentrated within a bandwidth of approximately 0.5 MHz indicating that the frequency chirp does not contribute substantially to the overall spectral width since the transform limit of the pulse (= inverse of the pulse duration) is of similar magnitude.
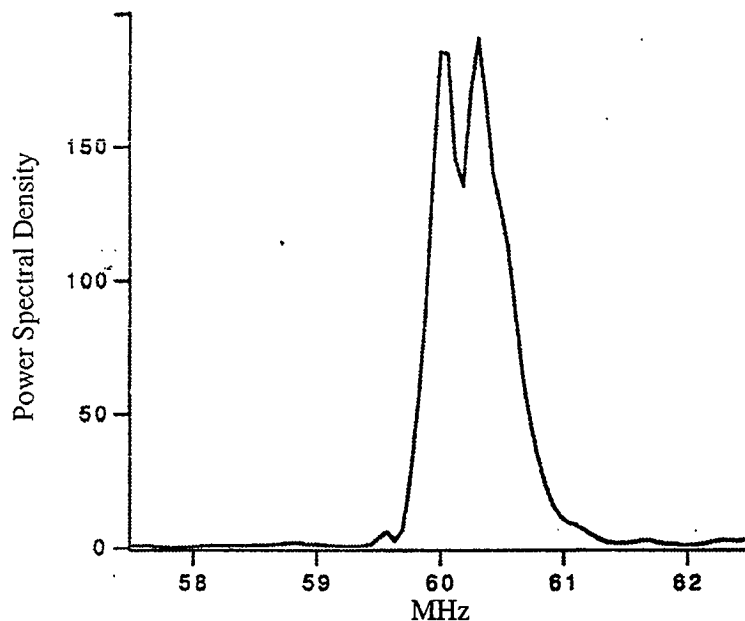
Figure 7-2 Power Spectral Density of Pulse Around 60 MHz

7.2 Life-test Program

The goals of the life-testing program included the evaluation of system life and reliability issues by performing long duration (large shot number) tests culminating in 10^8 shot duration runs using the STI Optronics-owned CO_2 Laser Testbed (CO2LT). The CO2LT is essentially a clone of the NOAA Windvan gain module manufactured by STI Optronics about a decade ago. It was fitted with an external catalyst loop to facilitate extended duration runs to investigate the laser chemistry at large shot number. Catalyst obtained from two sources (Langley Research Center and UOP Plc.) were used during the investigation. Both abundant and rare-isotope $^{12}C^{18}O_2$ gas were used.

A photograph of the CO2LT device with diagnostic systems in place is shown in Figure 7-3. The diagnostic systems in place include the following:
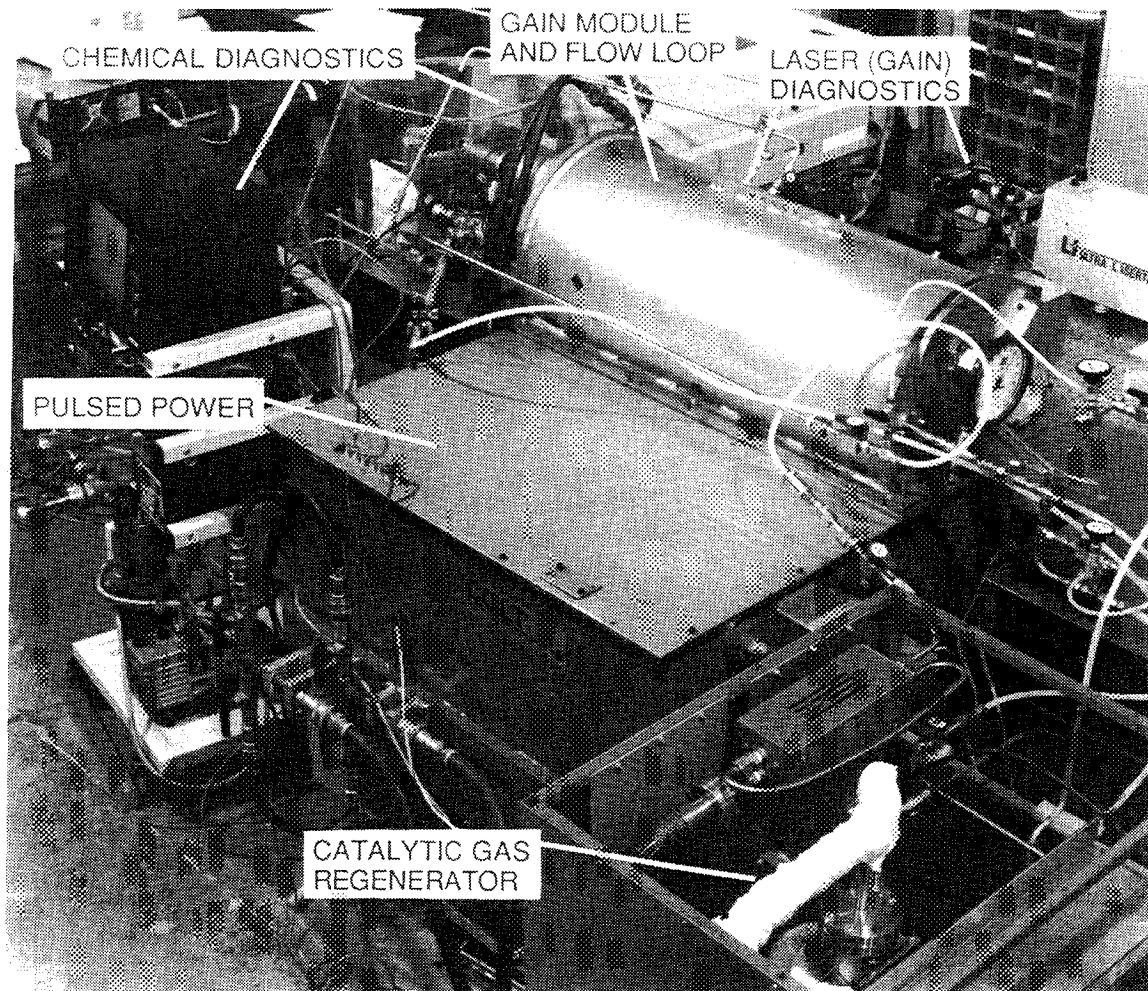
Figure 7-3. LAWS Life Test Bed

- A mass spectrometer used to periodically analyze a sample of the gas drawn from the laser cavity. This proved particularly useful in assessing the O_2 level in the gas mixture formed by dissociation of CO_2, and also in assessing the relative abundances of the various CO_2 isotopes during nominal rare isotope runs.

- A Nicolet Fourier Transform Infrared Spectrometer capable of performing *in-situ* laser cavity spectral analyses of the gas. This proved particularly useful in assessment of infrared active molecules, specifically CO, since its mass peak coincides with N_2 and makes the mass spectrometer reading ambiguous during abundant CO_2 isotope runs.

- A laser medium gain measurement set-up capable of *in-situ* monitoring of the single-pass gain along the axis of the gain module. It consists of an Ultralasertech CW laser beam that is propagated down the axis of the gain module and directed onto an infrared detector, where the increase in laser power during discharge excitation is measured.

- Measurement of discharge I-V curves to establish the laser discharge energy loading

The test program achieved 2 notable results:

- A 10^8 shot run using the abundant isotope and NASA LaRC catalyst. At the end of the run (terminated to allow experimentation with the rare isotope) the laser gain was in excess of 80% of its starting value.

- A 55-million shot run using the $^{12}C^{18}O_2$ isotope and gas self catalysis (homogeneous catalysis). The run was achieved with only a single precursor 10^7 shot run to passivate the system.

To our knowledge, the 10^8 shot run reported here is the first report of such a long-duration closed-cycle operation of a significant scale CO_2 laser. Also, the 55-million-shot run is to our knowledge the longest duration run for a repetitively pulsed CO_2 laser using the same gas mix and employing gas self-catalysis or homogeneous catalysis. Our conclusions and observations as a result of the life test program are as follows:

- Current designs of laser head components (corona bars, electrodes and insulators) demonstrated excellent reliability and resiliency.

- No build-up of impurities other than CO and O_2 was observed.

- Demonstration of gas self-catalysis during a long-duration run allows consideration of a laser without a catalyst monolith in the flow loop. This simplifies flow-loop design, reduces fan power requirements, eliminates catalyst monolith launch integrity concerns and decreases risk in general.

- The isotope scrambling issue is a manageable one for the LAWS program.

8.0 SUMMARY

LAWS has been a very successful program meeting most of the program goals set out in 1989.

The laser was rightly identified as the "tall-pole" in the technology of LAWS from the beginning; however, the coordinated program which was laid out in 1989, and which was largely funded, has put to rest the majority of these issues. Performance of the $C^{18}O_2$ molecule is not in question now the gas kinetics are understood. The chemistry of $C^{18}O_2$ has been shown to be the same as $C^{16}O_2$ thanks to the GE/STI funded gas chemistry program. The catalyst developed at LaRC demonstrated over 100 million shots on the LAWS lifetest breadboard. The lifetest breadboard has demonstrated 100 million shots on one gas fill and 55-million shots using gas self-catalysis. The new corona bar design is very reliable (~200 million shots without failure) and improves the discharge resulting in an increase in laser efficiency to the level required for space operation.

Early in the program it was realized that the telescope main bearing was a crucial element of the whole system both from the standpoint of performance and life. Any jitter or runout in the bearing produces rigid-body motion of the telescope which enters directly into the pointing error budget. An HDOS IR & D program demonstrated that the performance requirements for the bearing could be met and the availability of the Hughes bearing and power transfer assembly (used on their communication spacecraft) alleviated the concerns over lifetime.

Increasing the performance (i.e. the quantum efficiency) of the receiver detector is equivalent to transmitting more energy from the laser (both laser energy and detector quantum efficiency appear linearly in the SNR equation) yet requires no additional power from the system. Investment in receiver development was therefore looked upon as very beneficial to the program. The GE IR & D program started in 1989 increased the quantum efficiency of high bandwidth HgCdTe detectors 3 dB, equivalent in performance to transmitting a laser pulse of twice the energy.

The likely next step for LAWS is towards a downsized system with a lower energy laser and smaller aperture telescope. The investment in the program over the last 4 years has given rise to a set of tools which can be used very easily to perform system trades for such a system. At the same time as such a study is taking place the opportunity exists to build on the successful risk reduction program to retire residual risks and continue to gather data to enable the phase C/D decision to be made in the foreseeable future.